

The 125 GeV Higgs boson signal within the Complex NMSSM

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Abstract

While the properties of the 125 GeV Higgs boson-like particle observed by the ATLAS and CMS collaborations are largely compatible with those predicted for the Standard Model state, significant deviations are present in some cases. We, therefore, test the viability of a Beyond the Standard Model scenario based on Supersymmetry, the CP-Violating Next-to-Minimal Supersymmetric Standard Model, against the corresponding experimental observations. Namely, we identify possible model configurations in which one of its Higgs bosons is consistent with the LHC observation and evaluate the role of the explicit complex phases on both the mass and di-photon decay of such a Higgs boson. Through a detailed analysis of some benchmark points corresponding to each of these configurations, we highlight the impact of the CP-violating phases on the model predictions compared to the CP-conserving case.

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1 Introduction

In July 2012, the CMS and ATLAS experimental collaborations at the Large Hadron Collider (LHC) announced the observation of a new boson [1, 2], consistent with a Higgs particle, the last undiscovered object in the Standard Model (SM). The initial results were based on data corresponding to integrated luminosities of 5.1 fb^{-1} taken at $\sqrt{s} = 7 \text{ TeV}$ and 5.3 fb^{-1} at 8 TeV and the search was performed in six decay modes: $H \rightarrow \gamma\gamma$, ZZ , $Z\gamma$, WW , $\tau^+\tau^-$ and $b\bar{b}$. A $\sim 5\sigma$ excess of events with respect to the background was clearly observed in the first and second of these decay modes, while the remaining ones yielded exclusion limits well above the SM expectation. Both collaborations have since been regularly updating their findings [3, 4, 5, 6, 7], improving the mass and (so-called) ‘signal strength’ measurements.

In these searches, the magnitude of a possible signal is characterised by the production cross section times the relevant Branching Ratios (BRs) relative to the SM expectations in a given channel X , denoted by $R(X) = \sigma/\sigma_{\text{SM}} \times \text{BR}(X)/\text{BR}_{\text{SM}}(X)$ (i.e., the signal strength). According to the latest results released by the two collaborations after the collection of $\sim 20 \text{ fb}^{-1}$ of data [5, 6, 7], a broad resonance compatible with a 125 GeV signal is now also visible in the $WW \rightarrow 2l2\nu$ decay channel. The mass of the observed particle is still centered around 125 GeV but the measured values of its signal strength in different channels have changed considerably compared to the earlier results. These values now read

$$\begin{aligned} R(H \rightarrow \gamma\gamma) &= 0.78 \pm 0.28, \\ R(H \rightarrow ZZ) &= 0.91_{-0.24}^{+0.3}, \\ R(H \rightarrow WW) &= 0.76 \pm 0.21 \end{aligned}$$

at CMS, and

$$\begin{aligned} R(H \rightarrow \gamma\gamma) &= 1.65 \pm 0.35, \\ R(H \rightarrow ZZ) &= 1.7 \pm 0.5, \\ R(H \rightarrow WW) &= 1.01 \pm 0.31 \end{aligned}$$

at ATLAS. The bulk of the event rates comes from the gluon-gluon fusion channel [8]. Furthermore, the signal has also been corroborated by Tevatron analyses [9], covering the $b\bar{b}$ decay mode only, with the Higgs boson stemming from associated production with a W boson [8]. However, there the comparisons against the SM Higgs boson rates are biased by much larger experimental errors.

If the current properties of the observed particle are confirmed after an analysis of the full 7 and 8 TeV data samples from the LHC, they will not only be a clear signature of a Higgs boson, but also a significant hint for possible physics beyond the SM. In fact, quite apart from noting that the current data are not entirely compatible with SM Higgs boson production rates, while the most significant LHC measurements point to a mass for the new resonance around 125 GeV the Tevatron excess in the $b\bar{b}$ channel points to a range between 115 GeV and 135 GeV . While the possibility that the SM Higgs boson state has any of such masses would be merely a coincidence (as its mass is a free parameter), in generic Supersymmetry (SUSY) models the mass of the lightest Higgs boson with SM-like behaviour is naturally confined to be less than 180 GeV or so [10]. The reason is that SUSY, in essence, relates trilinear Higgs boson and gauge couplings, so that the former are of the same size as the latter, in turn implying such a small Higgs boson mass value. Therefore, the new LHC results could well be perceived as being in favour of some low energy SUSY realisation.

Several representations of the latter have recently been studied in connection with the aforementioned LHC and Tevatron data, including the Minimal Supersymmetric Standard Model (MSSM)

[11] (also the constrained version [12] of it, in fact), the Next-to-Minimal Supersymmetric Standard Model (NMSSM) [13, 14, 15], the E_6 -inspired Supersymmetric Standard Model (E_6 SSM) [16] and the (B-L) Supersymmetric Standard Model ((B-L)SSM) [17]. All of these scenarios can yield a SM-like Higgs boson with mass around 125 GeV and most of them can additionally explain the excesses in the signal strength measurements in the di-photon channel.

Another approach to adopt in order to test the viability of SUSY solutions to the LHC Higgs boson data is to consider the possibility of having CP-violating (CPV) phases (for a general review of CP Violation, see [18]) in (some of) the SUSY parameters. These phases can substantially modify Higgs boson phenomenology in both the mass spectrum and production/decay rates at the LHC [19, 20, 21, 22], while at the same time providing a solution to electroweak baryogenesis [23]. In the context of the LHC, the impact of CPV phases was emphasised long ago in [24, 25] and revisited recently in [26] following the Higgs boson discovery. In all such papers though, CPV effects were studied in the case of the MSSM.

In this paper, we consider the case of similar CPV effects in the NMSSM. In particular, we study the possibility to have Higgs boson signals with mass around 125 GeV in the CPV NMSSM which are in agreement with the aforementioned LHC data as well as the direct search constraints on sparticle masses from LEP and LHC. We also investigate the dependence of the feasible CPV NMSSM signals on the mass of the Higgs boson as well as its couplings to both the relevant particle and sparticle states entering the model spectrum, chiefly, through the decay of the former into a $\gamma\gamma$ pair. We thus aim at a general understanding of how such observables are affected by the possible complex phases explicitly entering the Higgs sector of the next-to-minimal SUSY Lagrangian.

The paper is organised as follows. In the next section we will briefly review the possible explicit CPV phases in the Higgs sector of the NMSSM. In Sect. 3 we will outline the independent CPV NMSSM parameters and the methodology adopted to confine our attention to the subset of them that can impinge on the LHC Higgs boson data. In the same section, we further investigate the possible numerical values of the complex parameters after performing scans of the low energy CPV NMSSM observables compatible with the LEP and LHC constraints on Higgs boson and SUSY masses. In Sect. 4 we present our results on the Higgs boson mass spectrum as well as signal rates in connection with the LHC. Finally, we conclude in Sect. 5.

2 CPV phases in the Higgs sector of the NMSSM

The CPV phases appearing in the Higgs potential of the NMSSM at tree-level [27] can be divided into three categories:

1. θ and φ : the spontaneous CPV phases of the vacuum expectation values (vevs) of the up-type Higgs doublet H_u and the Higgs singlet S , respectively, with respect to the down-type Higgs doublet H_d ;
2. ϕ_λ and ϕ_κ : the phases of the Higgs boson trilinear couplings λ and κ ;
3. ϕ_{A_λ} and ϕ_{A_κ} : the phases of the trilinear soft terms A_λ and A_κ .

As explained in [28, 29] the phases in 3. above are determined by the minimisation conditions of the Higgs potential with respect to the three Higgs fields. Furthermore, assuming vanishing spontaneous CPV phases in 1., the only actual physical phases appearing in the tree-level Higgs potential are those in 2. as the difference $\phi_\lambda - \phi_\kappa$. Beyond the Born approximation, the phases of the trilinear couplings A_t , A_b and A_τ also enter the Higgs sector through radiative corrections from the third generation squarks and stau (assuming negligible corrections from the first two generations).

Also, in the one-loop effective potential, each of the phases in 2. above contributes independently from the other. The complete one-loop Higgs mass matrix can be found in [28, 29, 30]. Here we only reproduce the tree-level Higgs as well as the sfermion mass matrices in Appendix A.

The 5×5 Higgs mass matrix \mathcal{M}_N^2 (after rotating out the Goldstone modes) is diagonalised with a unitary matrix O to yield five mass eigenstates as

$$(\phi_d^0, \phi_u^0, \phi_S^0, a, a_S)^T = O (H_1, H_2, H_3, H_4, H_5)^T, \quad (1)$$

where $O^T \mathcal{M}_N^2 O = \text{diag}(m_{H_1}^2, m_{H_2}^2, m_{H_3}^2, m_{H_4}^2, m_{H_5}^2)$ in order of increasing mass. For a non-zero value of any of the phases listed above, these mass eigenstates become CP-indefinite due to scalar-pseudoscalar mixing. Moreover, these CPV phases not only affect the masses of the Higgs states but also their decay rates (both widths and BRs), since the Higgs boson couplings to various particles are proportional to the elements of the unitary matrix O (see, e.g., [31, 32]). Additionally, modifications in the masses of light neutralinos, in particular, due to the CPV phases can also have an indirect yet non-negligible impact on the BRs of the Higgs boson into SM particles.

The decay widths and BRs of the Higgs boson in the NMSSM with CPV phases can be calculated using the methodology implemented in [31]. Explicit expressions for Higgs boson couplings and widths in the CPV NMSSM can be found in [33], which follows the notation of [34]. These widths and BRs can then be used to obtain the signal strength of the $\gamma\gamma$ channel (also called *reduced* di-photon cross section), $R_{H_i}^{\gamma\gamma}$, defined as

$$R_{H_i}^{\gamma\gamma} = \frac{\sigma(gg \rightarrow H_i)}{\sigma(gg \rightarrow h_{SM})} \times \frac{\text{BR}(H_i \rightarrow \gamma\gamma)}{\text{BR}(h_{SM} \rightarrow \gamma\gamma)}, \quad (2)$$

for a given Higgs boson, H_i . In terms of the reduced couplings $C_i(X)$ (couplings of H_i with respect to those of the SM Higgs boson with the same mass), eq. (2) can be approximated by

$$R_{H_i}^{\gamma\gamma} = [C_i(gg)]^2 [C_i(\gamma\gamma)]^2 \sum_X \frac{\text{BR}(H_i \rightarrow X)}{[C_i(X)]^2}, \quad (3)$$

where X runs over all possible decay modes of the Higgs boson in the SM.

3 Model parameters and methodology

In light of the recent LHC discovery of a SM Higgs boson-like boson we scan the parameter space of the CPV Higgs sector of the NMSSM using a newly developed FORTRAN code. In our scans the LEP constraints on the model Higgs bosons are imposed in a modified fashion, i.e., they have to be satisfied by the scalar and pseudoscalar components of all the CP-mixed Higgs bosons. Also imposed are the constraints from the direct searches of the third generation squarks, stau and the light chargino at LEP. We should also point out that, in the CPC limit, the Higgs boson mass and BRs have been compared with those given by NMSSMTools [35] and have been found to differ from the latter by $\sim 1\%$ and $\sim 5\%$ at the most, respectively. Although no limits from b -physics or from relic density measurements have been imposed we, nevertheless, confine ourselves to the regions of the parameter space which have been found to best comply with such constraints (see, e.g., [15]).

We study the effects of the CPV phases described in the previous section on the mass and di-photon signal rate of a Higgs boson predicted by the model that is compatible with the Higgs boson discovery data from the LHC. In particular, we consider three most likely scenarios specific to the CPV NMSSM that comply with the latter. In our analyses, we assume minimal Supergravity (mSUGRA)-like unification of the soft parameters at the SUSY-breaking energy scale, such that

$$\begin{aligned}
M_0 &\equiv M_{Q_3} = M_{U_3} = M_{D_3} = M_{L_3} = M_{E_3} = M_{\text{SUSY}}, \\
M_{1/2} &\equiv 2M_1 = M_2 = \frac{1}{3}M_3, \\
A_0 &\equiv A_t = A_b = A_\tau.
\end{aligned}$$

These parameters are then fixed to their optimal values based on earlier studies [13, 15] in order to minimise the set of scanned parameters. We then focus only on the effects of the Higgs sector parameters, which include the dimensionless Higgs boson couplings λ and κ along with their phases ϕ_λ and ϕ_κ , as well as the soft SUSY-breaking parameters A_λ and A_κ . From outside the Higgs sector, we only analyse the effect of the variation of the unified CPV phase of the third generation trilinear couplings, ϕ_{A_0} ($\equiv \phi_{A_t} = \phi_{A_b} = \phi_{A_\tau}$).

Before we discuss the three scenarios mentioned above, we note that the two heaviest Higgs boson mass eigenstates H_4 and H_5 always correspond to the interaction eigenstates ϕ_u^0 and a in eq. (1).¹ Hence, a scenario is defined by the Higgs state that conforms to the LHC observations, out of the three light mass eigenstates, H_1 , H_2 and H_3 , and by the correspondence between the latter and the interaction eigenstates ϕ_d^0 , ϕ_S^0 and a_S . However, note that such a definition is adopted only so that a distinction between different scenarios can be made conveniently. Evidently, the behaviour of the ‘observed’ Higgs boson, H_{sig} , with the CPV phases in a given scenario is a combined result of the set of parameters yielding that scenario rather than of its position among the mass-ordered Higgs states. The criteria for choosing the ranges of the scanned model parameters as well as the values of the non-Higgs-sector SUSY parameters thus depend on the scenario under consideration and are explained in the following.

Scenario 1: In this scenario the lightest Higgs state, H_1 , is the SM-like one and corresponds to ϕ_d^0 , while H_2 and H_3 correspond to ϕ_S^0 and a_S , respectively. The requirement of obtaining a down-type Higgs state with mass close to 125 GeV and with SM-like couplings necessitates large soft SUSY masses and A_0 . The values of μ_{eff} ($\equiv \lambda s$, where s is the vev of S) and the gaugino masses are found to be in best agreement with the relic density constraints [15], giving a neutralino with a large Higgsino component as the lightest SUSY particle. Further, λ and κ are chosen such that there is enough mixing of the doublet with the singlet Higgs boson so as to allow an H_1 with the correct mass while keeping its couplings close to their SM values. We test two cases for this scenario, corresponding to two representative values of the parameter $\tan\beta$ ($\equiv v_u/v_d$, where v_u and v_d are the vevs of H_u and H_d , respectively), which is fixed to 6 in Case 1 and to 15 in Case 2.

Scenario 2: This scenario is defined by the SM-like ~ 125 GeV Higgs boson being the second lightest Higgs boson, H_2 , of the model. There are two possibilities entailing such a scenario. It can correspond to ϕ_S^0 in which case it has $R_{H_i}^{\gamma\gamma}$ SM-like or bigger, as shown in [13]. We refer to this possibility as Case 1 of this scenario. It requires relatively large values of λ and κ , small values of the parameters A_λ and A_κ and moderate values of soft SUSY-breaking parameters. H_1 and H_3 in this case are ϕ_d^0 and a_S dominated, respectively. For Case 2 of this scenario, we take a slightly different region of the parameter space which yields a H_2 that is ϕ_d^0 -like and hence has $R_{H_2}^{\gamma\gamma}$ around the SM expectation. Hence, heavy unified soft squark mass and/or trilinear coupling are required in this case, but a light soft gaugino mass is preferred. λ can be small to intermediate while κ is always small. Finally, H_1 and H_3 are ϕ_S^0 - and a_S -like, respectively.

Scenario 3: There also exists the possibility that the observed ~ 125 GeV Higgs boson is the H_3 of the model which corresponds to ϕ_d^0 , while both ϕ_S^0 - and a_S -like Higgs bosons are lighter. Such a scenario can be realised for very fine-tuned ranges of the parameters A_λ and A_κ for a given $\tan\beta$

¹Implying that after diagonalisation of the Higgs mass matrix, e.g., ϕ_u^0 makes the dominant component of H_4 .

Scenario	1, Case 1	1, Case 2	2, Case 1	2, Case 2	3
Fixed parameters					
M_0 (TeV)	5		0.8	3	3
$M_{1/2}$ (TeV)	3		0.35	0.35	1.5
$-A_0$ (TeV)	10		1	4	4
μ_{eff} (TeV)	1		0.14	0.14	0.14
$\tan \beta$	6	15	1.9	20	10
Scanned parameters					
λ	0.01 – 0.1		0.5 – 0.6	0.01 – 0.3	0.1 – 0.3
κ	0.1 – 0.3		0.3 – 0.4	0.01 – 0.1	0.05 – 0.1
A_λ (TeV)	1.5 – 3		0.14 – 0.2	0.2 – 0.6	0.95 – 1.05
$-A_\kappa$ (TeV)	1 – 4		0.2 – 0.25	0.1 – 0.3	0.07 – 0.09

Table 1: Input parameters of the CPV NMSSM and their numerical values adopted in our analysis.

value, with large soft squark and gaugino mass parameters preferred. Note that in this case the a_S -like H_3 of Case 2 of Scenario 2 turns into H_2 by becoming lighter than the ϕ_d^0 -like state which, consequently, turns into H_3 . These two cases thus overlap slightly in terms of the relevant parameter space of the model.

We point out here that we do not consider a scenario with the ~ 125 GeV Higgs boson corresponding to the a_S interaction eigenstate, since the pure (or nearly pure) pseudoscalar hypothesis is disfavored by the CMS Higgs boson analyses [36, 37]. Values of the fixed parameters as well as ranges of the variable parameters for all the above scenarios are given in Tab. 1.

4 Scans and results

We perform scans for each of the scenarios described earlier requiring the mass of H_{sig} (i.e., of H_1 in Scenario 1, H_2 in Scenario 2 and H_3 in Scenario 3) to lie in the range $124 \text{ GeV} < m_{H_{\text{sig}}} < 127 \text{ GeV}$.² We additionally impose the condition $R_{H_{\text{sig}}}^{\gamma\gamma} > 0.5$ on the signal Higgs boson. Furthermore, to each case in a given scenario corresponds four scans, such that in each of the scans only one of the following (set of) phases is varied:

- (i) ϕ_κ , (ii) ϕ_λ , (iii) ϕ_{A_0} , (iv) ϕ_λ and ϕ_κ ,

while fixing the rest of the CPV phases to 0° . Each scan thus checks the effect of a different CPV source at the tree-level and/or beyond. Note that, since the phases ϕ_λ and ϕ_κ enter at the tree-level, the contributions from the terms dependent on them reverse sign for $\phi_\lambda, \phi_\kappa > 90^\circ$. This can lead to negative diagonal entries in the Higgs boson mass matrix, giving tachyonic mass eigenstates. On the other hand, ϕ_{A_0} does not have such a restriction and can yield physical masses even with values above 90° . However, for the sake of consistency, we only scan between $0^\circ - 90^\circ$ for all these phases. The relevant phase(s) is (are) varied in steps of 1° for scans (i)–(iii) above and in steps of 5° for scan (iv).

We should point out here that the measurements of the Electric Dipole Moment (EDM) of the electron, neutron and various atoms [38, 39, 40] put constraints on the allowed values of ϕ_λ and

²We thus use the central mass measurement of 125.5 GeV in accordance with the CMS results.

ϕ_{A_0} . However, the trilinear couplings of squarks and sleptons contribute to the EDMs only at the two-loop level and their phases are thus rather weakly constrained. One can, furthermore, assign very heavy soft masses to the sfermions of first two generations in order to minimize the effect of ϕ_{A_0} on the EDMs, as pointed out in earlier studies for the MSSM [41]. In fact, such constraints can be neglected altogether by arguing that the phase combinations occurring in the EDMs can be different from the ones inducing Higgs boson mixing [42]. The phase of κ , in contrast, has been found to be virtually unconstrained by the EDM measurements [32, 29].

Below we present our results separately for each of the five cases investigated. For evaluating the effect of the phases on $m_{H_{\text{sig}}}$ and $R_{H_{\text{sig}}}^{\gamma\gamma}$ qualitatively, we choose a set of four Representative Points (RPs), referred to as RP1, RP2, RP3 and RP4 in the following, for every scenario. RP1 corresponds to a point for which the effect of at least one out of the three phases ϕ_κ , ϕ_λ and ϕ_{A_0} on $m_{H_{\text{sig}}}$ is maximised for the given case. Similarly, RP2 is chosen such that the variation in $R_{H_{\text{sig}}}^{\gamma\gamma}$ is maximal with one of the phases. RP3 and RP4 are points with the largest affect on $m_{H_{\text{sig}}}$ and $R_{H_{\text{sig}}}^{\gamma\gamma}$, respectively, observed in our scans with simultaneous variation of ϕ_λ and ϕ_κ . Note that in the discussion below the description of the behaviour of a given RP may not be equally applicable to all other good points, since it is chosen so as to understand the maximum possible impact of the phase that is the most influential one for a given case. In particular, for different RP2 and RP4 in a given case, the roles of ϕ_λ and ϕ_κ could well be interchanged, since $R_{H_1}^{\gamma\gamma}$ depends dominantly on the a_S component of H_1 which is driven by a combination of λ and κ .

4.1 Scenario 1:

Case 1: In Fig. 1 (top-left) we show the variation in the number of good points, i.e., points surviving the conditions imposed on $m_{H_{\text{sig}}}$ and $R_{H_{\text{sig}}}^{\gamma\gamma}$, for this scenario with small $\tan\beta$ for varying ϕ_λ , ϕ_κ and ϕ_{A_0} . Fig. 1 (top-right) shows the corresponding variation with ϕ_λ and ϕ_κ changing simultaneously. The number of surviving points falls sharply with ϕ_{A_0} but relatively slowly with ϕ_λ and ϕ_κ . The variation is, however, not continuous since there are other parameters, λ , κ , A_λ and A_κ , which are also scanned over for every value of a given phase. Moreover, the number of good points evidently depends on the conditions on $m_{H_{\text{sig}}}$ and $R_{H_{\text{sig}}}^{\gamma\gamma}$, so while both of these may be satisfied for one value of a phase one of these may be violated for the next. This is especially true for points producing $m_{H_{\text{sig}}}$ and/or $R_{H_{\text{sig}}}^{\gamma\gamma}$ near the boundaries of their required ranges. Note that the CPC case is subject to these two conditions also and, on account of being defined relative to this case, the number of good points does not represent all possible solutions for all values of the phases. Thus, it is likely that the CPC case for a given parameter set falls outside the defined ranges of $m_{H_{\text{sig}}}$ and/or $R_{H_{\text{sig}}}^{\gamma\gamma}$, but the conditions on these are satisfied for a different value of a particular phase. Such a value of the phase can thus result in a considerable number of good points which were absent in the CPC case. Nevertheless, the aim here is to give an estimate of the effect of the CPV phases on the number of good points relative to the CPC case, rather than presenting a truly holistic picture. The values of other parameters corresponding to each RP for this Case are given below.

Point	λ	κ	A_λ (GeV)	A_κ (GeV)
RP1	0.1	0.11	3000	-1000
RP2	0.1	0.25	1500	-3000
RP3	0.05	0.11	2000	-4000
RP4	0.1	0.25	1500	-3000

Fig. 1 (middle-left) shows that the condition on $m_{H_{\text{sig}}}$ is the one mainly responsible for the drop

in the number of good points. In the figure we see m_{H_1} falling slowly with increasing ϕ_κ and ϕ_λ , more so for the former than the latter. The drop in m_{H_1} with increasing ϕ_{A_0} is relatively sharp. This is due to the fact that H_1 in this scenario is very ϕ_d^0 -like and the contribution from the singlet-like states is small since fairly small values of λ and κ are involved. Hence the phases of these parameters also have a lighter impact on m_{H_1} . On the other hand, in order to reach values up to 125 GeV, the mass of H_1 strongly relies on the trilinear coupling A_0 and is consequently also more sensitive to its phase. Fig. 1 (middle-right) shows the combined effect of ϕ_λ and ϕ_κ . We should point out again that at the tree-level only the difference $\phi_\lambda - \phi_\kappa$ enters, so a given combination of these phases can be mapped onto a particular value of ϕ_λ at the tree-level and should thus have the same effect. However, such a mapping is not possible when one includes higher order effects since at this level ϕ_λ and ϕ_κ appear independently of each other. The figure thus implies that the role of these phases is, expectedly, even smaller at the one-loop level. For small ϕ_λ larger values of ϕ_κ cause a bigger drop in m_{H_1} while for larger ϕ_λ a smaller ϕ_κ results in more deviation from the CPC case.

Bottom-left and -right panels in Fig. 1 correspond to RP2 and RP4, respectively, and show a fairly generic dependence of $R_{H_{\text{sig}}}^{\gamma\gamma}$ on the CPV phases for this scenario. We note that $R_{H_{\text{sig}}}^{\gamma\gamma}$ falls sharply with ϕ_λ and ϕ_κ , more so for the former than the latter, until it reaches a minimum value and then rises again. The observed behaviour is due to the variation in the $H_1 \rightarrow b\bar{b}$ width which increases sharply owing to the contribution from the a_S component of H_1 , for which the $b\bar{b}$ coupling gets enhanced faster than the scalar component. $\text{BR}(H_1 \rightarrow b\bar{b})$ thus reaches a peak and then starts dropping. Expectedly $R_{H_{\text{sig}}}^{\gamma\gamma}$ has negligible dependence on ϕ_{A_0} since the a_S component does not receive higher order corrections and thus does not have any dependence on A_0 and its phase, while for the ϕ_d component the variation in all BRs is almost constant when this phase is varied. RP4 in the figure on the right follows a trend similar to RP2, with $R_{H_{\text{sig}}}^{\gamma\gamma}$ showing greater variation compared to the CPC case for not too large values of ϕ_λ and ϕ_κ .

Case 2: For large $\tan\beta$ in this scenario the drop in the number of good points is even slower than in Case 1 as seen in Fig. 2 (top-left). For almost the entire range of ϕ_κ all the points satisfy the conditions imposed, while in case of ϕ_λ the number of good points falls quite abruptly around 75° and likewise for ϕ_{A_0} around 40° . A similar behaviour is observed in Fig. 2 (top-right) where the number of good points falls to 0 for $\phi_\lambda > 75^\circ$ irrespective of the value of ϕ_κ . The RPs for this Case are as follows.

Point	λ	κ	A_λ (GeV)	A_κ (GeV)
RP1	0.07	0.11	3000	-1000
RP2	0.1	0.25	1500	-3000
RP3	0.07	0.11	3000	-1000
RP4	0.07	0.28	1833	-3000

The sudden fall in the number of good points is, once again, largely driven by $m_{H_{\text{sig}}}$ which reaches its allowed lower limit gradually with increasing values of the phases as verified by Fig. 2 (middle-left and middle-right) for RP1 and RP3, respectively. The cut-off in the ϕ_κ line for RP1 is due to the sudden drop of $R_{H_{\text{sig}}}^{\gamma\gamma}$ below 0.5. Such a behaviour of $R_{H_{\text{sig}}}^{\gamma\gamma}$ is evident from Fig. 2 (bottom-left and bottom-right) for RP2 and RP4, respectively, where one sees that it remains almost constant before dipping sharply for some given particular values of ϕ_λ and ϕ_κ . This is again due to a sudden surge in the $H_1 b\bar{b}$ coupling and consequently in $\text{BR}(H_1 \rightarrow b\bar{b})$ which in turn causes $\text{BR}(H_1 \rightarrow \gamma\gamma)$ to diminish, even though the $H_1 \rightarrow \gamma\gamma$ width itself remains almost constant. Notice

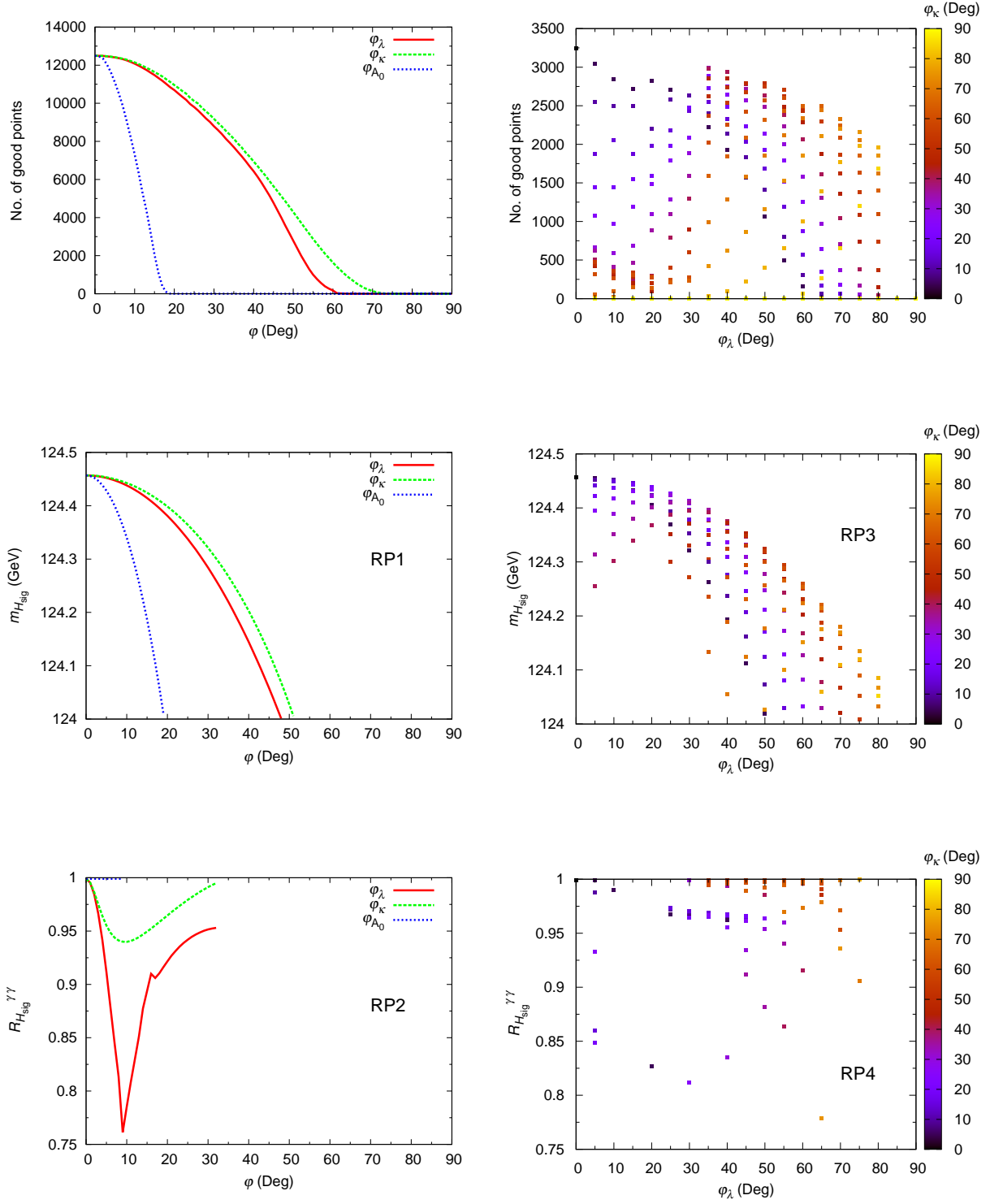


Figure 1: Distributions of good points, $m_{H_{\text{sig}}}$ and $R_{H_{\text{sig}}}^{\gamma\gamma}$ for Scenario 1, Case 1.

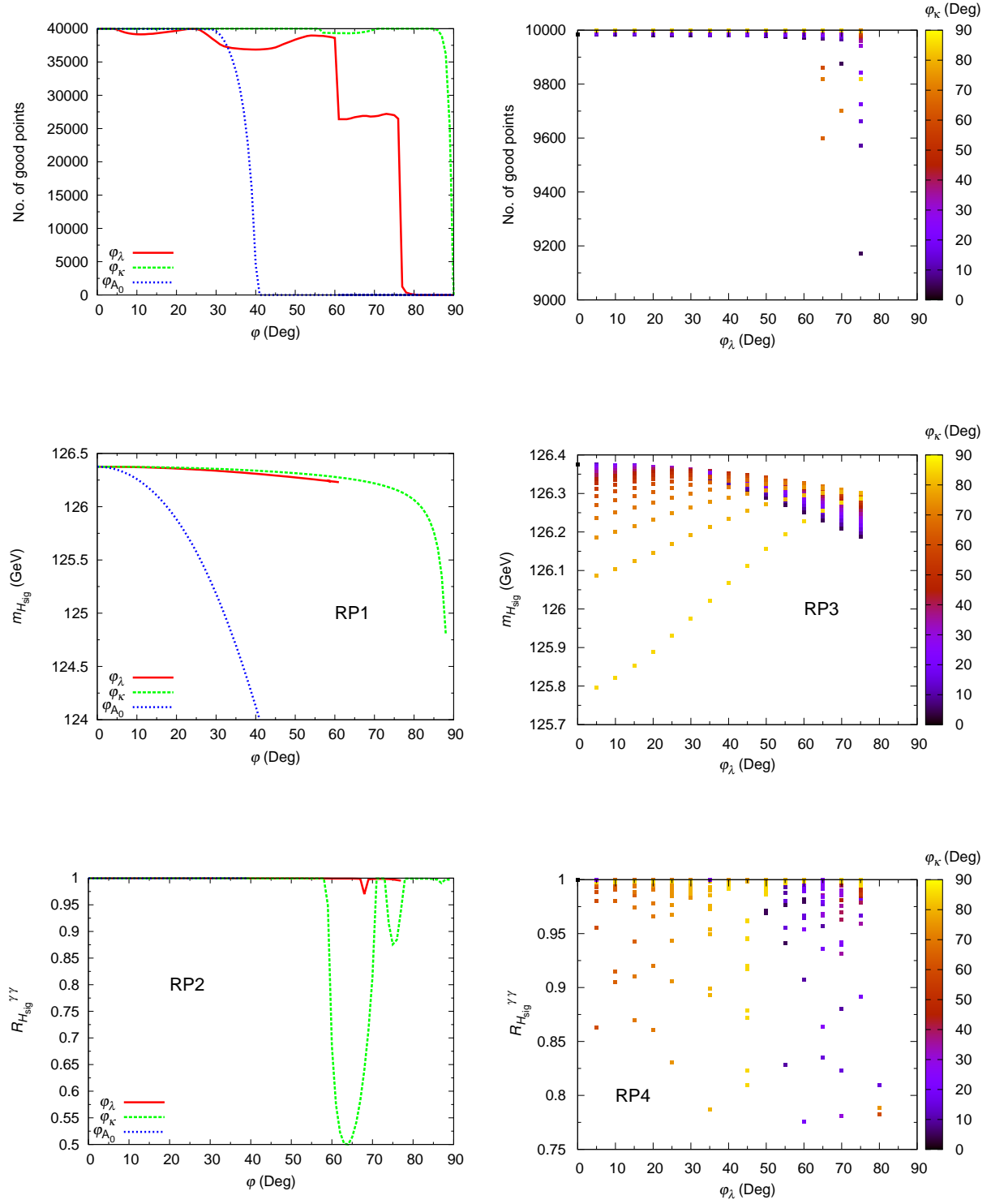


Figure 2: Distributions of good points, $m_{H_{sig}}$ and $R_{H_{sig}}^{\gamma\gamma}$ for Scenario 1, Case 2.

Scenario	1, Case 1	1, Case 2
Points scanned for each ϕ_κ or ϕ_λ or ϕ_{A_0}	40000	
Points surviving for $\phi_\kappa = \phi_\lambda = \phi_{A_0} = 0$	12494	39976
$m_{h_{\text{sig}}}$ for RP1 with $\phi_\kappa = \phi_\lambda = \phi_{A_0} = 0$	124.4570	126.3754
$R_{H_{\text{sig}}}^{\gamma\gamma}$ for RP2 with $\phi_\kappa = \phi_\lambda = \phi_{A_0} = 0$	0.9990	0.9997
Max. points surviving, with ϕ_κ	12494, 0	40000, 30-85
Max/min $m_{h_{\text{sig}}}$ obtained for RP1, with ϕ_κ	124.0058, 51	124.8054, 88
Max/min $R_{H_{\text{sig}}}^{\gamma\gamma}$ obtained for RP2, with ϕ_κ	0.9399, 10	0.5001, 64
Max. points surviving, with ϕ_λ	12494, 0	39976, 0-4
Max/min $m_{h_{\text{sig}}}$ obtained for RP1, with ϕ_λ	124.0009, 48	126.2300, 61
Max/min $R_{H_{\text{sig}}}^{\gamma\gamma}$ obtained for RP2, with ϕ_λ	0.7613, 9	0.9700, 68
Max. points surviving, with ϕ_{A_0}	12494, 0	39976, 0-3
Max/min $m_{h_{\text{sig}}}$ obtained for RP1, with ϕ_{A_0}	124.0117, 19	124.0015, 41
Max/min $R_{H_{\text{sig}}}^{\gamma\gamma}$ obtained for RP2, with ϕ_{A_0}	0.9990, 9	0.9998, 39
Points scanned for each pair of ϕ_κ and ϕ_λ	10000	
Points surviving for $\phi_\kappa = \phi_\lambda = \phi_{A_0} = 0$	3248	9983
$m_{h_{\text{sig}}}$ for RP3 with $\phi_\kappa = \phi_\lambda = \phi_{A_0} = 0$	124.4569	126.3753
$R_{H_{\text{sig}}}^{\gamma\gamma}$ for RP4 with $\phi_\kappa = \phi_\lambda = \phi_{A_0} = 0$	0.9990	0.9998
Max. points surviving, with $\phi_\kappa, \phi_\lambda$	3248, 0, 0	10000, 5-10, 30-85
Min $m_{h_{\text{sig}}}$ obtained for RP3, with $\phi_\kappa, \phi_\lambda$	124.0080, 75, 55	125.797, 5, 85
Min $R_{H_{\text{sig}}}^{\gamma\gamma}$ obtained for RP4, with $\phi_\kappa, \phi_\lambda$	0.7754, 60, 20	0.778, 115, 40

Table 2: Scan results for Scenario 1, Cases 1 and 2. All angles are in degrees.

that since $\tan \beta$ is large in this Case, the h_d^0 component of H_1 has an enhanced coupling to $b\bar{b}$ while its a_S component is strongly dependent on λ and κ as well as their phases. The combined effect of these two factors is that sensitivity of the $H_1 \rightarrow b\bar{b}$ decay to certain values of ϕ_λ and ϕ_κ is further enhanced through the relevant entry of the Higgs boson mixing matrix O .

We should mention here that H_2 and H_3 are always very heavy, ~ 2 TeV, for both the Cases of this scenario. Moreover, $R_{H_{\text{sig}}}^{ZZ}$ follows the same trend with the variation in CPV phases as $R_{H_{\text{sig}}}^{\gamma\gamma}$ and is in fact always almost equal to it. Some important numbers corresponding to these Cases and to the four RPs in each of these are provided in Tab. 2.

4.2 Scenario 2:

Case 1: In Fig. 3 (top-left) we show the number of good points vs. the CPV phases. We see that the number of surviving points in the CPC case is much smaller compared to the two Cases of Scenario 1. However, in contrast to the latter, it falls more sharply with ϕ_λ and ϕ_κ than with ϕ_{A_0} . In fact, no good points are obtained for $\phi_\lambda > 25^\circ$ when it is varied simultaneously with ϕ_κ , as seen in Fig. 3 (top-right). This significantly different dependence of the signal Higgs boson in this case is due to the fact that it is now ϕ_S -like. In order to obtain such a singlet-dominated Higgs boson with the correct mass and $\gamma\gamma$ rate, fairly large values of the parameters λ and κ are needed, which result in an increased sensitivity to their phases also. On the other hand, since both ϕ_S^0 and a_S states do not couple to matter, the only dependence on A_0 and its phase comes through the small

doublet component of H_2 . The particulars of the RPs for this Case are given below.

Point	λ	κ	A_λ (GeV)	A_κ (GeV)
RP1	0.51	0.34	187	-239
RP2	0.52	0.33	200	-233
RP3	0.578	0.33	160	-233
RP4	0.6	0.34	187	-211

Fig. 3 (middle-left) for RP1 further verifies our statement above. In the figure we see that $m_{H_{\text{sig}}}$ varies rapidly with ϕ_λ and ϕ_κ but very slowly with ϕ_{A_0} . In fact, $m_{H_{\text{sig}}}$ always lies within the allowed range for all values of ϕ_{A_0} for RP1 which, however, is also due to the fact that $m_{H_{\text{sig}}}$ is very close to the allowed upper limit in the CPC case. Notice also that $m_{H_{\text{sig}}}$ first falls sharply with increasing ϕ_κ and then rises again after reaching a minimum implying, again, that due to the large values of κ and λ , the composition of H_2 alters abruptly with these phases. H_1 in this Case is ϕ_d^0 -like and is mostly around 100 GeV while H_3 is a_S -like and around 300 GeV. Fig. 3 (middle-right) for RP3 shows that the combined effect of simultaneously increasing ϕ_λ and ϕ_κ is that $m_{H_{\text{sig}}}$ increases very sharply with them. In fact, as in Scenario 1, the mixing effects cause the mass of H_1 to fall with increasing values of the phases, which in turn results in H_2 gaining mass.

Another characteristic feature of Case 1 of this Scenario is the fact that $R_{H_{\text{sig}}}^{\gamma\gamma}$ can be fairly higher than the SM expectation and its dependence on ϕ_λ and ϕ_κ is opposite to that on ϕ_{A_0} . As shown in Fig. 3 (bottom-left) for RP2, while $R_{H_{\text{sig}}}^{\gamma\gamma}$ increases with ϕ_{A_0} , it falls abruptly with ϕ_λ and ϕ_κ . The reason is that, while $\text{BR}(H_2 \rightarrow \gamma\gamma)$ grows with both ϕ_κ and ϕ_{A_0} , $\text{BR}(H_2 \rightarrow gg)$, which is much more dominant, grows faster with ϕ_κ than with ϕ_{A_0} . Further, $\text{BR}(H_2 \rightarrow b\bar{b})$ remains almost constant with increasing values of the phases. In case of increasing ϕ_λ , on the other hand, $\text{BR}(H_2 \rightarrow \gamma\gamma)$ itself falls while both $\text{BR}(H_2 \rightarrow gg)$ and $\text{BR}(H_2 \rightarrow b\bar{b})$ grow. Evidently, with both ϕ_λ and ϕ_κ increasing simultaneously, $R_{H_{\text{sig}}}^{\gamma\gamma}$ falls quite rapidly, as seen in Fig. 3 (bottom-right) for RP4. Finally, $R_{H_{\text{sig}}}^{ZZ}$ in this Case is always slightly lower than $R_{H_{\text{sig}}}^{\gamma\gamma}$ (e.g., it is ~ 0.9 for RP2) but shows a similar behaviour with varying CPV phases.

Case 2: This Case corresponds to a ϕ_d^0 -like H_2 state but shows a somewhat different behaviour from Scenario 1. In this Case the fastest but non-smooth variation in the number of good points comes from ϕ_κ , as seen in the top-left panel of Fig. 4. Also, in contrast to Scenario 1, the number of good points, which is fairly low for the CPC case, rises slowly with increasing ϕ_{A_0} and then starts falling. In the top-right panel of the figure we see that when both ϕ_λ and ϕ_κ are varied simultaneously, the drop in the number of good points is very slow, much like it is when ϕ_λ is varied alone (left panel). Below we give the values of other Higgs sector parameters for the four RPs of this Case.

Point	λ	κ	A_λ (GeV)	A_κ (GeV)
RP1	0.047	0.14	600	-180
RP2	0.044	0.015	467	-147
RP3	0.04	0.012	556	-153
RP4	0.05	0.014	289	-160

The middle-left panel of Fig. 4 for RP1 shows that $m_{H_{\text{sig}}}$ rises continuously with increasing ϕ_κ and ϕ_λ , but falls with ϕ_{A_0} . The increase in mass of H_2 due to ϕ_λ and ϕ_κ is, in analogy with Case 1, due to the mixing effects with the a_S -like H_1 , whose mass falls with these phases. On the

other hand, since now H_2 itself is ϕ_d^0 -like, the dependence on A_0 and consequently on its phase is enhanced again, compared to the Case 1. We note here that m_{H_3} for the CPC case of RP1 is fairly small, ~ 180 GeV, and falls abruptly with ϕ_κ but rises slowly with ϕ_λ . The middle-right panel for RP3 shows that the simultaneous variation in ϕ_λ and ϕ_κ also results in a slow increase in the mass of H_2 . However, the difference in mass is maximised compared to the CPC case when one of the two phases has a small value while the other has a large value.

In the bottom panels of Fig. 4 we show the variation in $R_{H_{\text{sig}}}^{\gamma\gamma}$ with the CPV phases for RP2 and RP4 of this case. When CP is conserved in this Case $R_{H_{\text{sig}}}^{\gamma\gamma}$ is generally slightly lower than 1 (SM expectation) but sits well within the observed range reported in the latest results by the CMS collaboration [5]. Moreover, the variation with the CPV phases is comparatively slower than the Cases discussed so far, with the strongest dependence being on ϕ_κ . $R_{H_{\text{sig}}}^{\gamma\gamma}$ falls smoothly with ϕ_{A_0} but with increasing ϕ_λ it first rises slightly and then starts falling slowly. This is due to the fact that $\text{BR}(H_2 \rightarrow \gamma\gamma)$ itself falls with increasing ϕ_{A_0} and ϕ_κ but rises slowly with ϕ_λ . In addition, $\text{BR}(H_2 \rightarrow gg)$ also falls with ϕ_λ and ϕ_κ while $\text{BR}(H_2 \rightarrow b\bar{b})$ remains almost constant for these phases. However, $\text{BR}(H_2 \rightarrow ZZ)$ rises with ϕ_λ causing $R_{H_{\text{sig}}}^{\gamma\gamma}$ to fall beyond a certain value of the latter. In case of ϕ_{A_0} $\text{BR}(H_2 \rightarrow ZZ/WW)$ falls rapidly while $\text{BR}(H_2 \rightarrow b\bar{b})$, which is the most dominant of all BRs, rises faster, causing in turn $R_{H_{\text{sig}}}^{\gamma\gamma}$ to drop. For RP4 in the bottom-right panel, the combined effect of ϕ_λ and ϕ_κ is that $R_{H_{\text{sig}}}^{\gamma\gamma}$ falls slowly, except for small values of ϕ_λ and large values of ϕ_κ when it tends to rise but only minimally so. Once again, $R_{H_{\text{sig}}}^{ZZ}$ is very close to $R_{H_{\text{sig}}}^{\gamma\gamma}$ for RP2 and RP4 in this Case also and follows a similar trend in variation with an increase in any of the three CPV phases.

Some particular values corresponding to the benchmark points for the two Cases of this Scenario are given in Tab. 3.

4.3 Scenario 3:

Although, as noted earlier, the parameter space corresponding to this Scenario overlaps a little with the Case 2 of Scenario 2, some significant differences are noticeable. According to the top-left panel of Fig. 5 a considerably larger number of points survives the scans for the CPC case. The number of good points falls slowly with ϕ_{A_0} and ϕ_λ , more so for the former than the latter, but with increasing ϕ_κ it first rises slightly and then starts falling very slowly. When ϕ_λ and ϕ_κ are increased simultaneously, the drop is sharper than with the two phases varied individually, as seen in the top-right panel. The representative points of this Scenario have the following co-ordinates.

Point	λ	κ	A_λ (GeV)	A_κ (GeV)
RP1	0.216	0.09	983	-76.7
RP2	0.163	0.055	950	-70
RP3	0.189	0.05	983	-85.6
RP4	0.167	0.056	983	-87.8

The middle-left panel of Fig. 5 shows that, similarly to the Case 2 of Scenario 2, $m_{H_{\text{sig}}}$ increase with ϕ_λ and ϕ_κ (although now the former has the largest effect of the two) while it falls with increasing ϕ_{A_0} . However, as noted earlier, such a behaviour due to ϕ_λ and ϕ_κ is specific to this particular RP1 and may not be the same for a different RP1. In the middle-right panel of Fig. 5 for RP3 we see that, as with the corresponding point of Scenario 2, $m_{H_{\text{sig}}}$ rises as ϕ_λ and ϕ_κ increase simultaneously, showing maximum enhancement when both the phases have large values.

Scenario	2, Case 1	2, Case 2	3
Points scanned for each ϕ_κ or ϕ_λ or ϕ_{A_0}	40000		
Points surviving for $\phi_\kappa = \phi_\lambda = \phi_{A_0} = 0$	6017	8792	16701
$m_{h_{\text{sig}}}$ for RP1 with $\phi_\kappa = \phi_\lambda = \phi_{A_0} = 0$	126.8907	125.1155	125.9961
$R_{H_{\text{sig}}}^{\gamma\gamma}$ for RP2 with $\phi_\kappa = \phi_\lambda = \phi_{A_0} = 0$	1.25	0.8551	0.8701
Max. points surviving, with ϕ_κ	6017, 0	8792, 0	17011, 22
Max/min $m_{h_{\text{sig}}}$ obtained for RP1, with ϕ_κ	125.7728, 18	126.7120, 59	126.9878, 31
Max/min $R_{H_{\text{sig}}}^{\gamma\gamma}$ obtained for RP2, with ϕ_κ	1.2413, 13	0.8430, 16	0.8294, 60
Max. points surviving, with ϕ_λ	6017, 0	8792, 0	16701, 0
Max/min $m_{h_{\text{sig}}}$ obtained for RP1, with ϕ_λ	124.1719, 11	125.5718, 59	126.9616, 16
Max/min $R_{H_{\text{sig}}}^{\gamma\gamma}$ obtained for RP2, with ϕ_λ	1.2253, 8	0.8419, 57	0.8009, 39
Max. points surviving, with ϕ_{A_0}	6017, 0	9126, 16	16701, 0
Max/min $m_{h_{\text{sig}}}$ obtained for RP1, with ϕ_{A_0}	124.2631, 88	124.0073, 28	124.0672, 44
Max/min $R_{H_{\text{sig}}}^{\gamma\gamma}$ obtained for RP2, with ϕ_{A_0}	1.3067, 42	0.8280, 45	0.8683, 17
Points scanned for each pair of ϕ_κ and ϕ_λ	10000		
Points surviving for $\phi_\kappa = \phi_\lambda = \phi_{A_0} = 0$	1555	2141	3862
$m_{h_{\text{sig}}}$ for RP3 with $\phi_\kappa = \phi_\lambda = \phi_{A_0} = 0$	124.3536	124.8334	124.2729
$R_{H_{\text{sig}}}^{\gamma\gamma}$ for RP4 with $\phi_\kappa = \phi_\lambda = \phi_{A_0} = 0$	1.0609	0.8851	0.8899
Max. points surviving, with $\phi_\kappa, \phi_\lambda$	1555, 0, 0	2141, 0, 0	3862, 0, 0
Max $m_{h_{\text{sig}}}$ obtained for RP3, with $\phi_\kappa, \phi_\lambda$	126.8948, 25, 15	126.4176, 55, 55	126.9995, 40, 45
Min $R_{H_{\text{sig}}}^{\gamma\gamma}$ obtained for RP4, with $\phi_\kappa, \phi_\lambda$	0.5385, 20, 30	0.8426, 55, 30	0.5015, 20, 75

Table 3: Scan results for Scenario 2, Cases 1 and 2, and Scenario 3. All angles are in degrees.

We should point out here that in this Case the H_1 (almost always ϕ_S -like) is always lower than ~ 115 GeV and can be as low as 20 GeV while H_2 (mostly a_S -like) ranges between 70 GeV and 124 GeV (the upper limit is explicitly imposed in the scans).

In the bottom-left panel of Fig. 5 $R_{H_{\text{sig}}}^{\gamma\gamma}$ for RP2 is shown as a function of the various phases. Once again, in analogy with Case 2 of Scenario 2, the value of $R_{H_{\text{sig}}}^{\gamma\gamma}$ is slightly lower than the SM expectation. While it remains almost constant with ϕ_{A_0} , it falls slightly more sharply with ϕ_λ than with ϕ_κ . In case of increasing ϕ_{A_0} $\text{BR}(H_3 \rightarrow \gamma\gamma)$ itself falls slowly while $\text{BR}(H_3 \rightarrow b\bar{b})$ rises. With increasing ϕ_λ , on the other hand, while $\text{BR}(H_3 \rightarrow gg)$ and $\text{BR}(H_3 \rightarrow b\bar{b})$ both fall slowly, $\text{BR}(H_3 \rightarrow WW/ZZ)$ rises comparatively rapidly. A similar pattern is seen for ϕ_κ also, although there $\text{BR}(H_3 \rightarrow \gamma\gamma)$ itself rises minimally with increasing phase, hence resulting in a slower drop in $R_{H_{\text{sig}}}^{\gamma\gamma}$ compared to the case for ϕ_λ . In the bottom-right panel of Fig. 5 we show the effect on $R_{H_{\text{sig}}}^{\gamma\gamma}$ of simultaneously changing ϕ_λ and ϕ_κ for RP4 of this Scenario. We note that for large ϕ_λ and small ϕ_κ $R_{H_{\text{sig}}}^{\gamma\gamma}$ can be considerably lower than its value corresponding to the CPC case.

As with all the other Cases with a ϕ_d^0 -like H_{sig} , $R_{H_{\text{sig}}}^{ZZ}$ has similar values as $R_{H_{\text{sig}}}^{\gamma\gamma}$ when the CPV phases are zero and a similar behaviour when these phases are varied. Finally, some details relevant to the four RPs of this Scenario are given in Tab. 3.

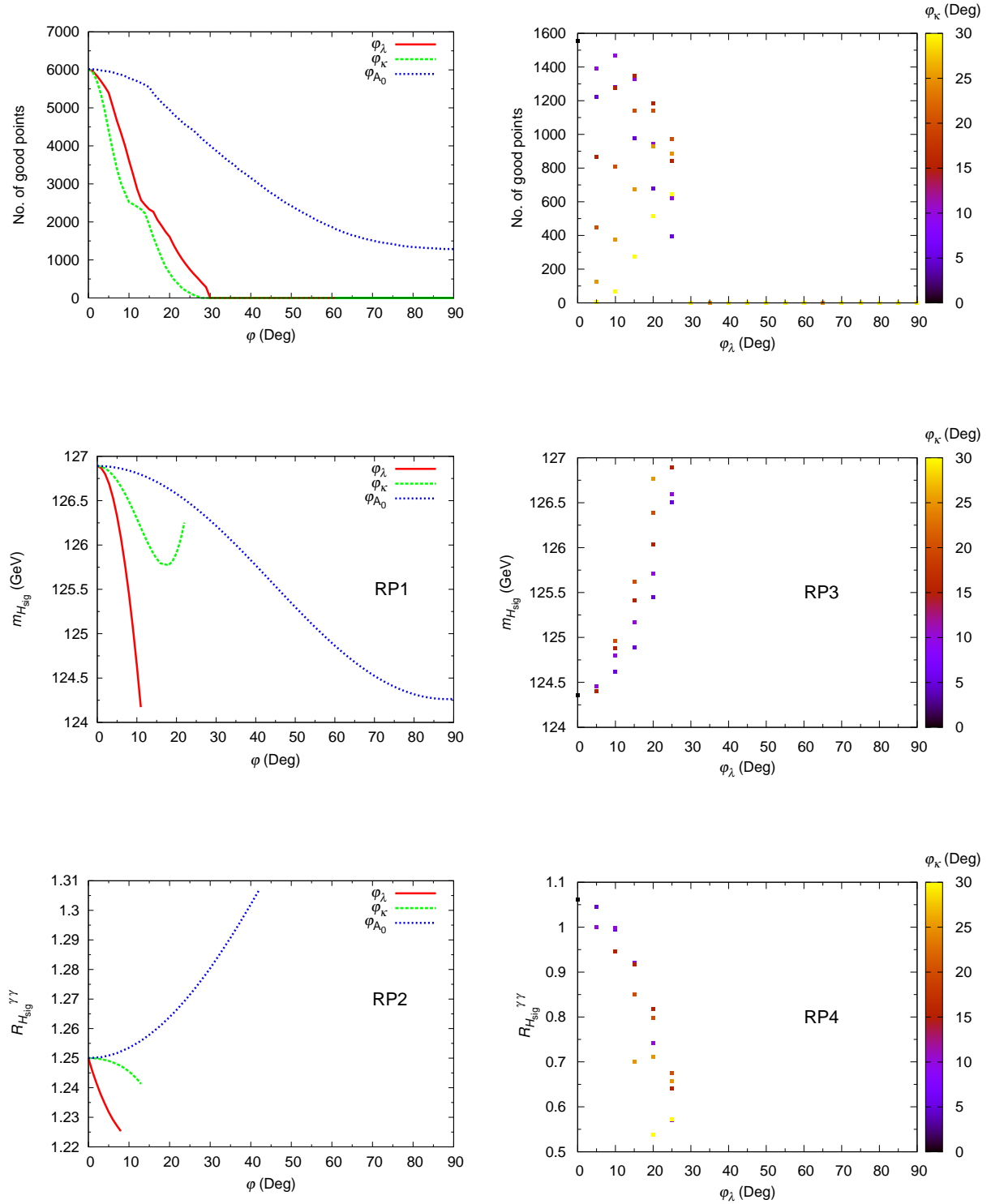


Figure 3: Distributions of good points, $m_{H_{sig}}$ and $R_{H_{sig}}^{\gamma\gamma}$ for Scenario 2, Case 1.

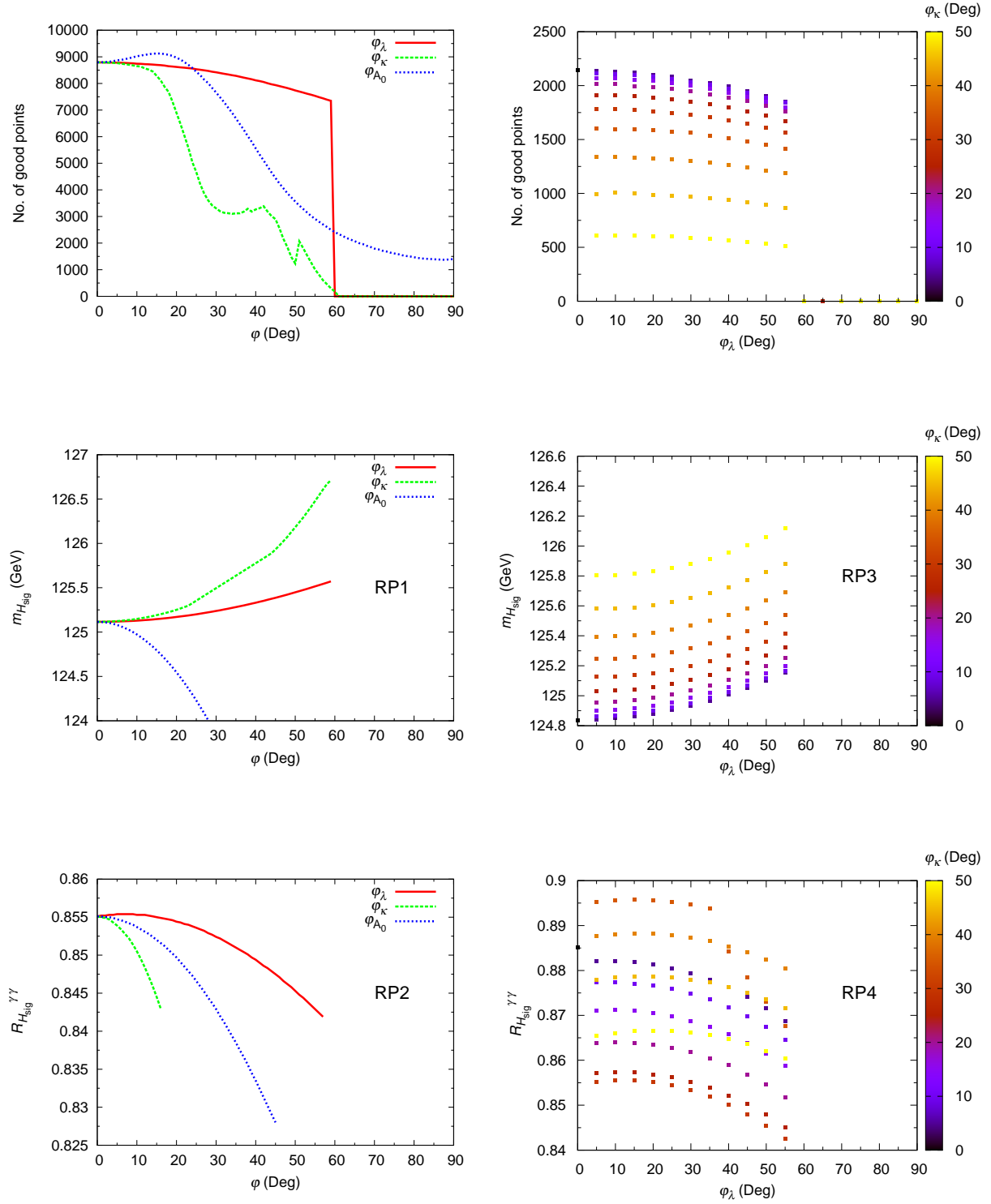


Figure 4: Distributions of good points, $m_{H_{sig}}$ and $R_{H_{sig}}^{\gamma\gamma}$ for Scenario 2, Case 2.

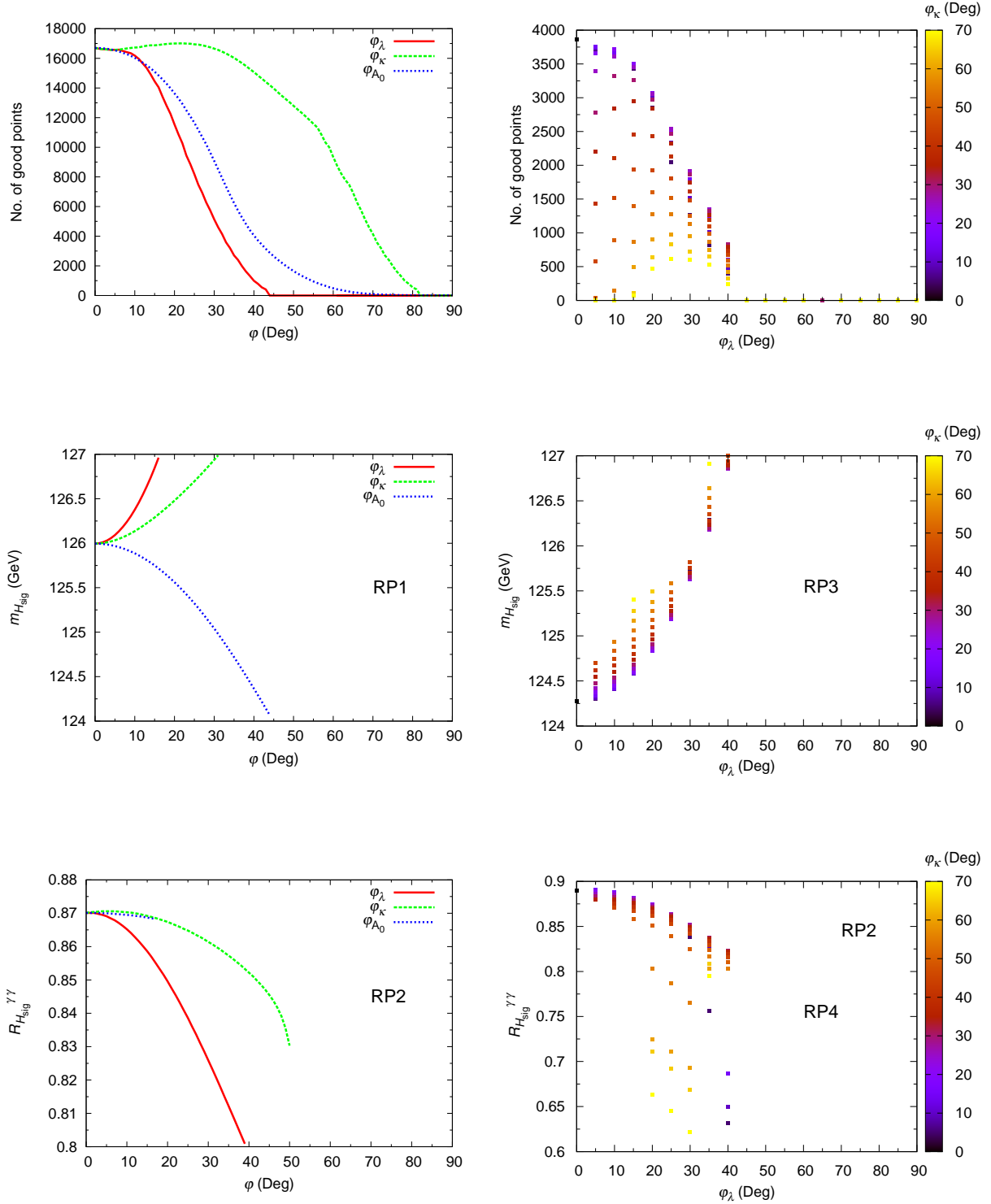


Figure 5: Distributions of good points, $m_{H_{sig}}$ and $R_{H_{sig}}^{\gamma\gamma}$ for Scenario 3.

5 Summary

In summary, we have demonstrated that the CPV NMSSM offers some interesting solutions to the LHC Higgs boson data, which differ substantially from well-known configurations of the CPC NMSSM, thereby augmenting the regions of parameter space which can be scrutinised at the CERN collider. We have concentrated on the case in which only three CPV phases, ϕ_κ , ϕ_λ and ϕ_{A_0} , enter the Higgs sector. We have then checked the two-fold impact of these phases, varied separately or simultaneously but always independently from each other, on the mass as well as signal strength of the assumed signal Higgs boson in the $\gamma\gamma$ decay mode, in different model configurations.

The overall picture that emerges is that any of the three lightest Higgs states of the CPV NMSSM can be the one discovered at the LHC. We have illustrated this by using five benchmark cases in the parameter space of the model that can easily be adopted for experimental analyses. Our analysis also proves that the possibility of explicitly invoking CPV-phases is not ruled out by the current LHC Higgs boson data in any of our tested plausible NMSSM scenarios. Finally, a numerical tool for analysing the Higgs sector of the CPV NMSSM has also been produced and is available upon request. Obvious outlook of this analysis will be to consider the possibility that companion Higgs boson signals to the one extracted at the LHC may emerge in the CPV NMSSM, so as to put the LHC collaborations in the position of confirming or disproving this SUSY hypothesis. An investigation on these lines is now in progress.

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A Mass Matrices

Detailed expressions for the one-loop Higgs boson mass matrices can be found in [28, 29, 30]. Here we only reproduce the tree-level mass matrix to show the dependence on ϕ_λ and ϕ_κ since the dominant contributions from these phases arise at this level. Note that the tree-level sfermion, neutralino and chargino mass matrices given below are complex by definition. The one-loop effective Higgs potential receives further contributions from ϕ_λ and ϕ_{A_0} through the squark and stau sectors and from ϕ_λ and ϕ_κ through the neutralino and chargino sectors.

- The neutral Higgs boson mass matrix may be written as:

$$\mathcal{M}_N^2 = \begin{pmatrix} \mathcal{M}_S^2 & \mathcal{M}_{SP}^2 \\ (\mathcal{M}_{SP}^2)^T & \mathcal{M}_P^2 \end{pmatrix}. \quad (\text{A.1})$$

Using the minimisation conditions of the Higgs potential, one can define some convenient parameters:

$$\begin{aligned} \mathcal{R} &= |\lambda||\kappa| \cos(\phi'_\lambda - \phi'_\kappa), & \mathcal{I} &= |\lambda||\kappa| \sin(\phi'_\lambda - \phi'_\kappa), \\ R_\lambda &= \frac{|\lambda||A_\lambda|}{\sqrt{2}} \cos(\phi'_\lambda + \phi_{A_\lambda}), & R_\kappa &= \frac{|\kappa||A_\kappa|}{\sqrt{2}} \cos(\phi'_\kappa + \phi_{A_\kappa}), \end{aligned} \quad (\text{A.2})$$

with

$$\phi'_\lambda \equiv \phi_\lambda + \theta + \varphi \quad \text{and} \quad \phi'_\kappa \equiv \phi_\kappa + 3\varphi. \quad (\text{A.3})$$

In terms of these parameters, the entries of the top left 3×3 CP-even block in eq. (A.1) are given as

$$\begin{aligned} (\mathcal{M}_S^2)_{11} &= \frac{g_2^2 + g_1^2}{4} v_d^2 + \left(R_\lambda + \frac{1}{2} \mathcal{R} v_S \right) \frac{v_u v_S}{v_d}, \\ (\mathcal{M}_S^2)_{22} &= \frac{g_2^2 + g_1^2}{4} v_u^2 + \left(R_\lambda + \frac{1}{2} \mathcal{R} v_S \right) \frac{v_d v_S}{v_u}, \\ (\mathcal{M}_S^2)_{33} &= R_\lambda \frac{v_d v_u}{v_S} + 2|\kappa|^2 v_S^2 - R_\kappa v_S, \\ (\mathcal{M}_S^2)_{12} &= (\mathcal{M}_S^2)_{21} = \left(-\frac{g_2^2 + g_1^2}{4} + |\lambda|^2 \right) v_d v_u - \left(R_\lambda + \frac{1}{2} \mathcal{R} v_S \right) v_S, \\ (\mathcal{M}_S^2)_{13} &= (\mathcal{M}_S^2)_{31} = -R_\lambda v_u + |\lambda|^2 v_d v_S - \mathcal{R} v_u v_S, \\ (\mathcal{M}_S^2)_{23} &= (\mathcal{M}_S^2)_{32} = -R_\lambda v_d + |\lambda|^2 v_u v_S - \mathcal{R} v_d v_S. \end{aligned} \quad (\text{A.4})$$

The bottom right 2×2 CP-odd block reads

$$\mathcal{M}_P^2 = \begin{pmatrix} (R_\lambda + \frac{1}{2} \mathcal{R} v_S) \frac{v^2 v_S}{v_d v_u} & (R_\lambda - \mathcal{R} v_S) v \\ (R_\lambda - \mathcal{R} v_S) v & R_\lambda \frac{v_d v_u}{v_S} + 2\mathcal{R} v_d v_u + 3R_\kappa v_S \end{pmatrix}. \quad (\text{A.5})$$

Finally, the entries of the off-diagonal block responsible for mixing between CP-even and CP-odd states is given as

$$\mathcal{M}_{SP}^2 = \begin{pmatrix} 0 & -\frac{3}{2} \mathcal{I} v_u v_S \\ 0 & -\frac{3}{2} \mathcal{I} v_d v_S \\ -\frac{3}{2} \mathcal{I} v_u v_S & -\frac{3}{2} \mathcal{I} v_d v_S \end{pmatrix}. \quad (\text{A.6})$$

- The chargino mass matrix, in the $(\widetilde{W}^-, \widetilde{H}^-)$ basis, using the convention $\widetilde{H}_{L(R)}^- = \widetilde{H}_{d(u)}^-$, can be written as

$$\mathcal{M}_C = \begin{pmatrix} M_2 & \sqrt{2} M_W \cos \beta \\ \sqrt{2} M_W \sin \beta & \frac{|\lambda| v_S}{\sqrt{2}} e^{i(\phi_\lambda + \theta + \varphi)} \end{pmatrix}, \quad (\text{A.7})$$

which is diagonalised by two different unitary matrices as $C_R \mathcal{M}_C C_L^\dagger = \text{diag}\{m_{\widetilde{\chi}_1^\pm}, m_{\widetilde{\chi}_2^\pm}\}$, where $m_{\widetilde{\chi}_1^\pm} \leq m_{\widetilde{\chi}_2^\pm}$.

- The neutralino mass matrix, in the $(\widetilde{B}, \widetilde{W}^0, \widetilde{H}_d^0, \widetilde{H}_u^0, \widetilde{S})$ basis, can be written as

$$\mathcal{M}_N = \begin{pmatrix} M_1 & 0 & -M_Z \cos \beta s_W & M_Z \sin \beta s_W & 0 \\ & M_2 & M_Z \cos \beta c_W & -M_Z \sin \beta c_W & 0 \\ & & 0 & -\frac{|\lambda| v_S}{\sqrt{2}} e^{i(\phi_\lambda + \theta + \varphi)} & -\frac{|\lambda| v_S \beta}{\sqrt{2}} e^{i(\phi_\lambda + \theta + \varphi)} \\ & & & 0 & -\frac{|\lambda| v \cos \beta}{\sqrt{2}} e^{i(\phi_\lambda + \theta + \varphi)} \\ & & & & \sqrt{2} |\kappa| v_S e^{i(\phi_\kappa + 3\varphi)} \end{pmatrix}. \quad (\text{A.8})$$

It is diagonalised as $N^* \mathcal{M}_N N^\dagger = \text{diag}(m_{\widetilde{\chi}_1^0}, m_{\widetilde{\chi}_2^0}, m_{\widetilde{\chi}_3^0}, m_{\widetilde{\chi}_4^0}, m_{\widetilde{\chi}_5^0})$, where N is a unitary matrix and $m_{\widetilde{\chi}_1^0} \leq m_{\widetilde{\chi}_2^0} \leq m_{\widetilde{\chi}_3^0} \leq m_{\widetilde{\chi}_4^0} \leq m_{\widetilde{\chi}_5^0}$.

- For the stop, sbottom and stau matrices, in the $(\tilde{q}_L, \tilde{q}_R)$ basis, we have

$$\begin{aligned}\widetilde{\mathcal{M}}_t^2 &= \begin{pmatrix} M_{\tilde{Q}_3}^2 + m_t^2 + \cos 2\beta M_Z^2 (\frac{1}{2} - \frac{2}{3}s_W^2) & h_t^* v_u (A_u^* e^{-i\theta} - \frac{|\lambda|v_S}{\sqrt{2}} e^{i(\phi_\lambda + \varphi)} \cot \beta) / \sqrt{2} \\ h_t v_u (A_u e^{i\theta} - \frac{|\lambda|v_S}{\sqrt{2}} e^{-i(\phi_\lambda + \varphi)} \cot \beta) / \sqrt{2} & M_{\tilde{U}_3}^2 + m_t^2 + \cos 2\beta M_Z^2 Q_t s_W^2 \end{pmatrix}, \\ \widetilde{\mathcal{M}}_b^2 &= \begin{pmatrix} M_{\tilde{Q}_3}^2 + m_b^2 + \cos 2\beta M_Z^2 (-\frac{1}{2} + \frac{1}{3}s_W^2) & h_b^* v_d (A_b^* - \frac{|\lambda|v_S}{\sqrt{2}} e^{i(\phi_\lambda + \theta + \varphi)} \tan \beta) / \sqrt{2} \\ h_b v_d (A_b - \frac{|\lambda|v_S}{\sqrt{2}} e^{-i(\phi_\lambda + \theta + \varphi)} \tan \beta) / \sqrt{2} & M_{\tilde{D}_3}^2 + m_b^2 + \cos 2\beta M_Z^2 Q_b s_W^2 \end{pmatrix} \quad (\text{A.9}) \\ \widetilde{\mathcal{M}}_\tau^2 &= \begin{pmatrix} M_{\tilde{L}_3}^2 + m_\tau^2 + \cos 2\beta M_Z^2 (s_W^2 - 1/2) & h_\tau^* v_d (A_\tau^* - \frac{|\lambda|v_S}{\sqrt{2}} e^{i(\phi_\lambda + \theta + \varphi)} \tan \beta) / \sqrt{2} \\ h_\tau v_d (A_\tau - \frac{|\lambda|v_S}{\sqrt{2}} e^{-i(\phi_\lambda + \theta + \varphi)} \tan \beta) / \sqrt{2} & M_{\tilde{E}_3}^2 + m_\tau^2 - \cos 2\beta M_Z^2 s_W^2 \end{pmatrix},\end{aligned}$$

where y_t , y_b and y_τ are the Yukawa couplings of t , b quarks and τ lepton, respectively, and $s_W = \sin \theta_W$. These sfermion mass matrices are diagonalised by unitary matrices U^f such that $U^{f\dagger} \widetilde{\mathcal{M}}_f^2 U^f = \text{diag}(m_{f_1}^2, m_{f_2}^2)$ with $m_{f_1}^2 \leq m_{f_2}^2$ for $f = t, b$ and τ .

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